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Rake Face Temperature when Machining with Coated Cutting Tools

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Abstract

Infrared thermography through transparent cutting tools has been used to measure the chip-tool interface temperature. It is of interest to extend this technique to study changes in interface temperature when tool coatings are used. An initial attempt is made here to measure the chip-tool interface temperature distribution when cutting Ti6Al4V with a TiN coated YAG tool. The TiN coating thickness is kept low at about 100 nm to minimize the temperature difference between the front (chip-TiN interface) and the back (TiN-YAG interface) faces of the coating. The transparency of the YAG tool allows near infrared radiation emitted by the back face of the TiN coating to be imaged. A novel method is used to measure the emissivity of the TiN/YAG interface. Using this method, and the available blackbody calibration of the temperature vs. intensity response of the imaging system, the images are converted into temperature maps. The performance of the coated tool is also evaluated in terms of machining force and tool wear characteristics. Coatings that remain intact during the experiments will reduce ambiguity in interpretation of the results.

Keywords: Machining, tool coatings, tool temperature, thermography.

1 Introduction

This paper introduces an extension of infrared thermography through transparent cutting tools for evaluation of the performance of machining tool coatings in terms of the temperature distribution that develops at the tool rake face. The technique consists of the application of an industrially relevant coating on an optically transparent material having the shape of a cutting tool. The temperature at the interface between coating and tool is then measured by *in situ* imaging of visible and near infrared radiation emitted. The coating is made sufficiently thick to withstand the cutting, yet thin enough that the temperature at the chip-coating interface is essentially the same as the temperature directly measured at the coating underside. Unlike other methods of tool temperature measurement that

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measure point-wise or average temperatures close to the interface, this technique provides the actual chip-tool interface temperature distribution that controls coating wear. In principle, the measurements can be performed for any industrial-grade tool coating or material. This technique is demonstrated here using titanium nitride (TiN) as coating material and yttrium aluminum garnet (YAG) as cutting tool body. For the demonstration, the workpiece material was annealed titanium alloy Ti6Al4V.

As the chip slides across the coated rake face, a thermographic system is used to image the radiation emitted by the coating underside (the side in contact with the tool), as shown in Figure 1. Following calibration with a blackbody, the radiation is then converted to temperature. For the conversion, the emissivity of the coating material must be known. The novel approach makes use of the reflection of the tool rake face on the tool flank face, which is also coated, to determine the coating emissivity *in situ*. The coating is sufficiently thin that the temperature difference across its thickness is negligible. Thus, the temperature at the chip-coating interface is virtually directly measured. This statement was justified using a simple one-dimensional heat transfer model. To ensure accuracy for the target temperature of about 1250 K, near infrared (visible) thermography was actually used, as explained by Lane et al., and Menon and Madhavan (Lane, Whitenton, Madhavan, & Donmez, 2013; Menon & Madhavan, 2014).

Attempts to measure temperature at the actual point where heat is generated in machining date back to the works of Shore (Shore, 1925) and Herbert (Herbert, 1926), who introduced the tool-work thermocouple technique. Among different methods that have been implemented since then stand out thermometry by the use of embedded thermocouples (Kitagawa, Kubo, & Maekawa, 1997), metallographic analysis (Wright & Trent, 1974; Smart & Trent, 1975) and radiometry, which in turn can be subdivided into pyrometry and infrared and near infrared thermography (Boothroyd, 1963; Jaspers, Dautzenberg, & Taminiau, 1998; Kus, Isik, Cemal Cakir, Coskun, & Özdemir, 2015; Lane, Whitenton, Madhavan, & Donmez, 2013; Menon & Madhavan, 2014). The tool-work thermocouple technique is based on the existence of a thermoelectric effect at the chip-tool interface, provided that the workpiece and the tool materials are dissimilar. It can only measure the mean temperature at the chip-tool interface. While it is possible to place many thermocouples very close to the chip-tool interface (embedded thermocouples) to determine temperature distribution at this interface (Komanduri & Hou, 2001), the installation of these thermocouples can be cost intensive and extremely tedious. More importantly, multiple holes have to be drilled, which alters the heat conduction through the tool and reduces its strength. Metallographic techniques infer the chip-tool interface temperature from microstructural or hardness changes in the chip material directly in contact with the tool. Even though this method is capable of measuring temperature within ±25 K in the range of 900 K to 1150 K (Wright & Trent, 1974), it is only applicable to tool materials whose microstructural change is very sensible to temperature, such as high speed steels.

In thermography, the radiation emitted by different points of a hot source in the infrared or near infrared portion of the spectrum can be converted into source temperature using a power law in the form (Menon & Madhavan, 2014; Menon, 2013):

$$T = a\left(\frac{S}{\varepsilon\tau}\right)^b \tag{1}$$

where T is the temperature of a particular point on the object (in Kelvin, K), S is a measure of the radiation intensity reaching the camera pixel where the object point is imaged, also known as the "counts" and expressed in arbitrary units, ε is the emissivity of the object's surface (dimensionless), and τ is the camera exposure time (in milliseconds, ms). The constants in Equation 1 are obtained after calibration with a blackbody placed directly on top of the tool rake face. The calibration procedure has been well described by Menon and Madhavan (Menon & Madhavan, 2014; Menon, 2013). If the radiation is measured with a high speed camera, thermography can return the temperature distribution of the source surface with high spatial and temporal resolution. This technique has been used to investigate the temperature distribution of the cutting tool (Miller, Mulholland, & Anderson, 2003; Narayanan, Krishnamurthy, Chandrasekar, Farris, & Madhavan, 2001), the workpiece (Boothroyd,